Physiological and Phenotypic Characteristics of Late Survivors of Tetralogy of Fallot Repair Who Are Free From Pulmonary Valve Replacement

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Background—Pulmonary valve replacement (PVR) after repair of tetralogy of Fallot is commonly required and is burdensome. Detailed anatomic and physiologic characteristics of survivors free from late PVR and with good exercise capacity are not well described in a literature focusing on the indications for PVR.

Methods and Results—Survival and freedom from PVR were tracked in 1085 consecutive patients receiving standard tetralogy of Fallot repair in a single institution from 1964 to 2009. Of 152 total deaths, 100 occurred within the first postoperative year. Surviving patients between 10 and 50 years of age had an annual risk of death of 4 (confidence limit, 2.8–5.4) times that of normal contemporaries. To date, 189 patients have undergone secondary PVR at mean age of 20±13 years (36% of those alive at 40 years of age). A random sample of 50 survivors (age, 4–57 years) free from PVR underwent cardiovascular magnetic resonance, echocardiography, and exercise testing. These patients had mildly dilated right ventricles (right ventricular end-diastolic volume=101±26 mL/m²) with good systolic function (right ventricular ejection fraction=59±7%). Most had exercise capacity within normal range (v peak V O₂=−0.91±1.3; v Ve/vCO₂=0.20±1.5). In patients >35 years of age with normal exercise capacity, there was mild residual right ventricular outflow tract obstruction (mean gradient, 24±13 mm Hg), pulmonary annulus diameters <0.5z, and unobstructed branch pulmonary arteries.

Conclusions—An important proportion of patients require PVR late after tetralogy of Fallot repair. Patients surviving to 35 years of age without PVR and with a normal exercise capacity may have had a definitive primary repair; their right ventricular outflow tracts are characterized by mild residual obstruction and pulmonary annulus diameter <0.5z. (Circulation. 2013;128:1861-1868.)

Key Words: cardiac surgery ▪ exercise tolerance ▪ magnetic resonance imaging ▪ tetralogy of Fallot
time of survivors who were free from secondary pulmonary valve implantation. Second, we closely examined 50 patients, 4 to 57 years of age, chosen at random from those who were stable without PVR to provide balance to the literature on late Fallot physiology, which is derived largely from patients who are being actively considered for PVR. Finally, we focused on patients >35 years of age who were free from secondary PVR and whose exercise capacity was within the normal range in hopes of defining the postoperative morphology and physiology that suggest the primary repair was definitive.

Methods

We created a complete consecutive list of all patients undergoing repair of uncomplicatedToF at the Great Ormond Street Hospital from February 1964 to January 2009. We excluded patients with absent pulmonary valve, pulmonary atresia, or atriocentric septal defect; those receiving an extracardiac conduit at their first repair; and patients from outside the United Kingdom whose follow-up we do not manage. Early postoperative deaths and the dates of any childhood PVRs were documented from operation notes. Consistently since 1996, all UK patients have a unique identifier, their National Health Service (NHS) number, which links to national death certification records; dates of death are registered in the NHS record when death occurs. Using batch tracing and manual searches and the known dates of birth and childhood surnames of patients discharged or lost before 1996, we attempted to establish the NHS numbers for the whole cohort. At 16 years of age, patients are currently discharged from our pediatric center to the care of their nearest adult congenital heart disease service. The Adult Congenital Heart Disease Research Network (ACoRN) represents each UK specialist adult congenital heart disease center. Collaborators from ACoRN scanned their local databases for the listed patients to ascertain whether they were under active review, had died under their care, or had undergone PVR. Patients who were recorded as relocating abroad or whose NHS numbers we could not match were censored on the date last seen alive to avoid any assumptions about their current status. The common closing date for data retrieval was January 2011. Patients who had corresponding NHS numbers but were not seen by adult congenital heart disease centers were recorded as alive but assumed not to have had PVR because this operation is undertaken only in specialist hospitals. The local Research Ethics Committee approved the project; this included the use of retrospective patient data and NHS number information without patient consent. For the 50 patients recruited prospectively into the physiological studies, informed consent was obtained.

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Survival and Proportions Free From PVR

Kaplan-Meier methodology was used to describe survival. To establish the excess hazard in the age frame of 10 to 50 years related to having survived Fallot repair for at least 1 year, we compared the risk of death in 5-year intervals for the Fallot cohort compared with deaths in the normal population sourced from the UK interim life tables for 1996, weighting the life table to correspond to the sex proportion in Fallot births. A proportional hazards model was used to explore the effect of operative era (decade of surgery) on late death; only patients alive 1 year postoperatively were entered into the analysis, and subsequent survival duration originated on that date. We used life table methodology to generate a graphic showing the changing proportions over time of patients in 3 mutually exclusive states: dead without PVR, alive with no PVR, and had PVR. SPSS version 18 was used.

Physiology of Patients Free From PVR

Using a random number generator, we chose 10 patients from each surgical decade (1960s to 2000s) from the list of those who were at least 1 year from surgery and had not had subsequent PVR. These patients were invited to return as volunteers to represent patients without PVR. This sample size was based on our previous study; 10 patients in each of 5 decade groups would be sufficient to detect a gradient of 0.14 per decade in RV/left ventricular volume ratio or 1.68 per decade in Ve/vo2 with 80% power (2 sided with 5% level of significance). We established from their operation notes whether the patients had received a transannular patch. Each patient underwent detailed cardiac magnetic resonance (MR) imaging, echocardiography, ECG, cardiopulmonary exercise testing, and serum brain natriuretic peptide level measurement as follows.

Cardiovascular Magnetic Resonance Imaging

Cardiovascular MR (CMR) was performed with a 1.5-T MR scanner (Avanto, Siemens Medical Systems) using techniques previously described. All volume and flow measurements were indexed to body surface area and compared with published normal values.

For the 5 children <8 years of age, the regression equations generated from normal subjects 8 to 17 years of age were used. Gadolinium contrast-enhanced MR angiography and 3-dimensional steady-state free precession imaging were used to obtain isotropic 3-dimensional images and to delineate the pulmonary artery anatomy. The diameters of the hinge points of the pulmonary valve were measured in diastole with two 2-dimensional outflow tract cine images acquired in the RV outflow tract (RVOT) in orthogonal planes. The 2 cross-sectional diameters were averaged.

Cardiopulmonary Exercise Testing

Cardiopulmonary exercise testing was performed by patients >9 years of age on an electronically braked bicycle ergometer (Ergoline 900) with respiratory gas exchange analysis. We used a ramp protocol as previously described. Peak oxygen uptake (peak V02), V02 at the anaerobic threshold, and ventilatory response to carbon dioxide production (Ve/vo2) were derived from respiratory gas analysis during maximal exercise testing; Ve/vo2 was measured as slope for the whole exercise.

Echocardiography

Standard Doppler echocardiography was performed with a VIVID 7 machine (GE Medical Systems, Milwaukee, WI) equipped with a multifrequency transducer (3.5 and 5 MHz) as previously described. From the same apical view, right and left atrial areas and tricuspid annulus diameters were measured and indexed for body surface area. Tricuspid annular plane systolic excursion was obtained from M-mode interrogation of the lateral aspect of the tricuspid valve. Right and left atrial filling pressures were obtained from the ratio of the transtricuspid and transmitral early diastolic velocities and early myocardial velocities measured at the lateral atriocentric valve annulus. Doppler tracing was taken during the patient’s breath hold. Peak velocity gradient across the RVOT was calculated from the maximum velocity obtained from the continuous-wave Doppler signal. The percentage collapse of the inferior vena cava diameter was measured from sagittal subcostal views during forced inspiration. Images were digitally stored for offline analysis with Echopac software (GE Vingmed, Horthen, Norway). All measurements were averaged from 3 consecutive cardiac cycles.

The CMR, cardiopulmonary exercise testing, and echocardiography parameters were rendered, when applicable, as z scores so that data could be summarized across the wide age range. Comparisons between groups were made with t tests, and hypotheses were rejected at P<0.05.
Definitive Repairs

Finally, we hypothesized that patients who have reached 35 years of age without PVR and who have objectively measured exercise tolerance within the normal range (peak $\dot{V}O_2 >-2\text{z}$) may never need surgical RVOT revision. However, they may yet experience myocardial or electrophysiological complications of their underlying condition or its treatment. To characterize the phenotype of repaired hearts that meet these stringent criteria of late function, we prepared volume-rendered CMR images of the 14 of 48 patients who fulfilled these criteria and underwent MR imaging scan.

Results

From February 1964 to January 2009, 1085 UK patients (58% male) had repair of ToF at the Great Ormond Street Hospital at a mean age of 3.5±3.6 years (range, 3 days to 18 years). For the 1085, we have either a known date of death or an NHS number indicating current survival status in all but 35; 60% of the 35 patients we have failed to track are female, suggesting that marital name changes may undermine tracing. Figure 1 summarizes the current status of the whole cohort.

One hundred fifty-two patients are known to have died to date. One hundred died within 1 year of repair (24 of 106 patients [23%] operated on in the 1960s compared with 6 of 246 [2%] operated on in the 2000s). Given the 1-year postoperative survival, subsequent survival was not demonstrably related to era (decade of surgery, $P=0.57$) or to age at repair ($P=0.84$). Twenty-six of the 52 deaths (50%) that have occurred beyond the first postoperative year appear not to have happened while the patient was under specialist care, making any summary of the causes of late death for this cohort unreliable. Across the age range of 10 to 50 years, patients face an estimated 4-fold (confidence limit, 2.8–5.4) increased annual probability of death compared with contemporaries of the same age drawn from the normal population.

PVR has been performed to date in 189 patients at a mean age 20±13 years, all of whom are under specialist care. There were 7 deaths within 3 months of these operations, although only 2 occurred when the operations had been done in an elective rather than an urgent context. One hundred forty patients underwent their first PVR at >10 years of age and thus received adult-sized valve at the time of reoperation. To date, 10 of these valves have needed rereplacement at a median interval of 9 years after first PVR. Figure 2 shows the changing proportion over time of patients in 3 mutually exclusive states: dead with no PVR, alive with no PVR, and had PVR.
Physiology of Patients Without PVR

Characteristics of the 50 patients (10 from each decade) selected at random from the list of patients who had not received PVR is shown in Table 1. Two patients 27 and 50 years of age underwent elective PVR within 6 months of these investigations.

CMR Results

CMR was performed in all but 2 volunteers: 1 patient had a pacemaker (male; age, 53 years), and another scan was terminated because the patient felt claustrophobic (female; age, 36 years). Our findings are summarized in Table 2, which displays mean values, indexed when appropriate, and Figure 3 shows individual results as z scores to summarize findings over the wide range of current ages. Overall, RV end-diastolic and end-systolic volumes were mildly larger than normal (z=1.8±2.3 and 1.8±3.0, respectively; P<0.0001), whereas left ventricular volumes and biventricular systolic function were predominantly within the normal range. A moderate degree of pulmonary regurgitation was common. For the group as a whole, the degree of pulmonary regurgitation was positively associated with pulmonary annulus diameter estimated at CMR (P<0.001, r=0.48), and those repaired with a transannular patch had significantly more pulmonary regurgitation than those without a transannular patch (31±14% versus 16±13%; P<0.005).

Exercise Testing

Of the volunteers tested (all >8 years of age), only 8 of 44 had reduced objectively measured exercise capacity compared with normal subjects (Table 2 and Figure 3).

Echocardiographic Results

Throughout the age range, there was significant dilatation (>2z compared with normal values) of right atrial areas and correspondingly of the indexed tricuspid valve annulus diameters. Older patients exhibited the highest values for these indexes, but because the patients documented by this cross-sectional process represent a smaller proportion of the whole group as time from surgery increases, we cannot infer that these parameters increase longitudinally with age.

For the group as a whole, velocity across the RVOT was slightly increased (mean, 2.2±0.6 m/s). RV tricuspid annular plane systolic excursion, a simple measure of RV ejection fraction, was globally reduced, although the mean for the group is still within 2 SD (z=−1.8±1.4). Tricuspid valve regurgitation was absent or mild in most patients, moderate in 1 patient, and severe in 2 patients. The indicators of RV

### Table 1. Clinical Characteristics of 50 Patients Divided by Surgical Decade

<table>
<thead>
<tr>
<th>Decade of Operation</th>
<th>1960s (n=10)</th>
<th>1970s (n=10)</th>
<th>1980s (n=10)</th>
<th>1990s (n=10)</th>
<th>2000s (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male/female, n</td>
<td>6/4</td>
<td>4/6</td>
<td>5/5</td>
<td>7/3</td>
<td>5/5</td>
</tr>
<tr>
<td>Age at operation, y</td>
<td>9.7±2.3</td>
<td>4.5±3.4</td>
<td>2.0±1.2</td>
<td>1.5±1.1</td>
<td>0.7±0.3</td>
</tr>
<tr>
<td>Age at study, y</td>
<td>52.5±3.3</td>
<td>38.6±5.2</td>
<td>27.9±4.0</td>
<td>17.3±4.1</td>
<td>7.7±2.2</td>
</tr>
<tr>
<td>Transatrial/transpulmonary approach</td>
<td>0/10</td>
<td>0/10</td>
<td>0/10</td>
<td>6/4</td>
<td>7/3</td>
</tr>
<tr>
<td>Transannular patch (yes/no), n</td>
<td>1/9</td>
<td>3/7</td>
<td>3/7</td>
<td>2/8</td>
<td>7/3</td>
</tr>
<tr>
<td>Previous palliation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L or R BT shunt</td>
<td>6</td>
<td>4</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Waterston shunt</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>NYHA class*</td>
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<td>I</td>
<td>9</td>
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<tr>
<td>III</td>
<td>2</td>
<td>1</td>
<td></td>
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</tbody>
</table>

BT indicates Blalock-Taussig; and NYHA, New York Heart Association.

*One 50-year-old patient and one 27-year-old patient underwent a pulmonary valve replacement within 6 months of the study.

### Table 2. CMR, Echo, and Exercise Results in Patients (4–58 Years of Age) Selected at Random From Those Without PVR

<table>
<thead>
<tr>
<th>HR, bpm</th>
<th>78±14</th>
</tr>
</thead>
<tbody>
<tr>
<td>QRS duration, ms</td>
<td>132±24</td>
</tr>
<tr>
<td>BNP, pg/mL</td>
<td>171±130</td>
</tr>
<tr>
<td>RV EDV, mL/BSA</td>
<td>101±26</td>
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<tr>
<td>RV ESV, mL/BSA</td>
<td>42±16</td>
</tr>
<tr>
<td>RV EF, %</td>
<td>59±7</td>
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<tr>
<td>LV EDV, mL/BSA</td>
<td>73±16</td>
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<tr>
<td>LV EF, %</td>
<td>64±6</td>
</tr>
<tr>
<td>PR, %</td>
<td>21±15</td>
</tr>
<tr>
<td>Peak vo, mL·kg⁻¹·min⁻¹</td>
<td>27±8</td>
</tr>
<tr>
<td>IC/e, slope</td>
<td>28±5</td>
</tr>
<tr>
<td>IVC collapse, %</td>
<td>81±23</td>
</tr>
<tr>
<td>RVOT velocity, m/s</td>
<td>2.2±0.6</td>
</tr>
<tr>
<td>TAPSE, mm</td>
<td>16.9±2.8</td>
</tr>
<tr>
<td>TV E/e'</td>
<td>0.9±0.5</td>
</tr>
<tr>
<td>MV E/e'</td>
<td>0.9±0.4</td>
</tr>
</tbody>
</table>

MRI, n=48; exercise parameters, n=44; and echocardiographic parameters, n=50. BNP indicates brain natriuretic peptide; BSA, body surface area; CMR, cardiac magnetic resonance; EDV, end-diastolic volume; EF, ejection fraction; ESV, end-systolic volume; HR, heart rate; IVC, inferior vena cava; LV, left ventricular; MV, mitral valve; PR, pulmonary regurgitant fraction; PVR, pulmonary valve replacement; RV, right ventricular; RVOT, right ventricular outflow tract; TAPSE, tricuspid annular plane systolic excursion; and TV, tricuspid valve.
and left ventricular filling pressures were within normal limits (tricuspid valve E/e’=0.9±0.5; mitral valve E/e’=0.9±0.4). Inferior vena cava collapse was reduced compared with normal (mean, 81±23%).

Phenotype of Primary Definitive Repair
Of the 17 patients >35 years of age who were free from late PVR, 14 exercised within the normal range. Figure 4 shows 3-dimensional volume-rendered models from MR

Figure 3. Summary of parameters for randomly selected patients free of secondary pulmonary valve replacement (PVR). Shaded areas correspond to normal range by age, displayed as ±2. Two patients 28 and 51 years of age subsequently underwent PVR. LVEF indicates left ventricular ejection fraction (%); PR, pulmonary regurgitant fraction (%); proBNP, pro-brain natriuretic peptide; PV diaz, pulmonary valve diameter z score; RA areaz, right atrial area z score; RVOTvel, right ventricular outflow tract velocity (m/s); RV TAPSEz, right ventricular tricuspid annular plane systolic excursion z score; and TV diaz, tricuspid valve diameter z score.
angiography, illustrating the morphology of the RVOTs of 12 of these 14 (2 patients did not undergo MR imaging). Three of the 14 had undergone transannular patching at the time of their primary repair, and 6 others had valvotomy or valvectomy. All 14 were free from either significant outflow tract aneurysm or significant branch pulmonary artery stenosis. All but 1 patient had some residual RVOT obstruction (group mean Doppler-estimated gradient, 24 mm Hg; range, 6–50 mm Hg; SD, 13 mm Hg). All but 1 patient had pulmonary regurgitation, but the degree of regurgitation was mild or moderate (regurgitant fraction group mean, 18%; range, 3%–39%; SD, 12%). Only 1 of the patients >35 years of age who exercised normally had an estimated pulmonary valve diameter >0.5; this patient was the individual with the worst pulmonary regurgitation (39%; Figure 5).

Discussion
This study confirms that patients undergoing ToF repair have good long-term survival. However, after 40 years, 36% of survivors have undergone PVR, and the proportion is even higher (58%) in those under active specialist follow-up. To date, there is no ideal substitute pulmonary valve; therefore, many patients having PVR can expect to be burdened from further procedures. Each reintervention carries a risk comparable to the mortality we would currently quote for the primary repair, so aggregated over a lifetime, the consequences of committing a patient at the time of their initial operation to later PVR are significant. Minimizing the burden of late PVR for patients requires addressing 2 uncertainties: how late-adult outcomes should affect decisions made at the time of primary repair and issues about the indications for late PVR.

A rigorous answer to either uncertainty is constrained by the enormous problems for any study design that are presented by the interval—often decades—between the intervention (here tetralogy repair) and an outcome (perhaps PVR). Our unusual study design contributes to the common surgical decision about how best to leave an imperfect RVOT at the end of a primary repair. In essence, morbidity related to early RV hypertension is associated with leaving too small a pulmonary annulus, and late problems of RV dilatation may be related to leaving one that is too large. By adding the perspective of data from late outcomes that have been exceptionally successful to what is already known about how to avoid early problems, we hoped to offer some tentative guidance about the size of annulus with or without transannular patch that may be optimal from a whole-life perspective.

That an element of residual RVOT obstruction may protect against late RV dilatation is suggested by Yoo et al., who used CMR to assess 190 patients with repaired ToF and found that patients with residual RVOT obstruction (mean gradient, 34±10.0 mm Hg) had less RV volume overload and no medium-term deterioration of RV function compared with those with predominant pulmonary regurgitation. Van der Hulst and colleagues also demonstrated that mild residual pulmonary stenosis reduced the need for PVR in 171 patients with ToF repair over a follow-up of 24 years. None of the patients in our own institution who required PVR for RVOT dysfunction from 2004 through 2007 had any residual RVOT obstruction (mean gradient, 16±1.4 mm Hg), and all had dilated RVOTs.

However, the surgical decision is difficult. RVOT gradients can be measured after discontinuation of bypass but are known to shift postoperatively, and the degree of late pulmonary regurgitation is hard to gauge unless the valve is unusually excellent. In practice, surgeons commonly use nomograms intraoperatively to guide decisions about when to insert a transannular patch; the absolute values charted in these nomograms describe pulmonary annulus diameters of normal hearts guarded by competent pulmonary valves. Guidelines vary, but a recent series has documented that leaving an annulus smaller than −1.3; is associated with a 25% chance of a late gradient of >30 mm Hg, and the authors suggest that a transannular patch be used to enlarge these outflow tracts if the annulus is “significantly” smaller than this. But how large should the patch be? Given what is known about the protective value of some residual obstruction when the valve is also regurgitant, it seems likely that the ideal pulmonary annulus after Fallot repair will be smaller than 2.0; If we could be confident that the pulmonary valve annulus did not grow or shrink disproportionately with somatic growth, it would be tempting to note that virtually all of our patients >35 years of age with normal exercise capacity and no PVR have some degree of residual RVOT obstruction (no more than mild) and have current pulmonary valve z scores <0.5, suggesting that pulmonary annulus with or without transannular patching should be no bigger than this at the end of the repair. Unfortunately, the trajectory of pulmonary annulus growth under the various permutations of primary repair is poorly documented at present, and our data on the pulmonary valve annulus at the time of our patients’ repairs are patchy, so these recommendations are necessarily provisional.

Figure 5. Relationship of pulmonary regurgitation (PR; %) to pulmonary valve (pv) diameter z score. Highlighted are the individuals aged >35 years whose cardiopulmonary exercise tests are within normal limits.
The debate about indications for secondary PVR requires longitudinal data, and our cross-sectional study cannot contribute directly to this. However, much of the available literature on the postoperative physiology of ToF focuses on patients investigated in the context of consideration of PVR. Patients in our data set were formally selected at random to represent those who remain free from PVR. Our review confirms that most have only mildly dilated RVs with good systolic function. These results are mirrored by a general clinical well-being (median New York Heart Association class, I) and normal exercise capacity for the majority of patients. On echocardiography, however, RV tricuspid annular plane systolic excursion was globally reduced, although still within 2 SD (z = −1.8±1.4), suggesting that this echocardiographic parameter might be a sensitive marker of mild, subclinical cardiac dysfunction. Our data could help to power further the formal observational or randomized studies that are needed to clarify the indications for PVR.

Limitations
Data linkage has been possible for all but 35 of our 1085 patients. The proportions of these 35 patients who may have died, moved abroad, or changed their names or whose original data were incorrect are unknown, and we have censored them when last seen alive to avoid introducing bias in the estimates we provide. The cardiac status of the patients not under adult congenital heart disease follow-up may be better than, worse than, or similar to those who are, although we have no particular indication that their original loss to follow-up was informative in this respect. The reasons for and impact of loss to follow-up are addressed elsewhere. In addition, patients with the worst anatomy may be underrepresented in the earliest surgical era because some may not have survived to or through open heart repair despite palliation. Furthermore, Awori et al have reflected on the pitfalls related to the variety of benchmarks for estimating pulmonary valve z scores; we have chosen to use echocardiography-derived parameters, although others have argued for using normal ranges derived from autopsy or transplantation normal ranges.

Conclusions
Although patients with repaired ToF have good long-term survival, a high proportion of patients require reintervention (PVR) at a relatively young age. A significant number of patients are free from reintervention and have preserved systolic function and normal exercise capacity up to 45 years after their initial repair. These patients, whose initial repair has proved long-lasting, have specific anatomic and functional characteristics that may reflect both an ideal anatomic substrate and optimal surgical therapy.

Our focus on patients who have avoided late PVR after ToF repair aimed to contribute late outcome data that might influence decisions made early in a patient’s management. As is common in pediatric cardiac surgical practice, important clinical decisions may have to be made using a combination of data, inference, and conjecture that is less than ideal. However, until we know more about annulus growth, it may be prudent to suggest that the ideal pulmonary annulus diameter with or without a transannular patch after Fallot repair should be between −1.3 and 0.5z.

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Disclosures
None.

References


**CLINICAL PERSPECTIVE**

This article provides an account of the long-term survival (>45 years of follow-up) of a large, complete, consecutive cohort of patients with repaired tetralogy of Fallot from a single UK institution. Using the functionality of a unique identifier, the National Health Service number, we were able to locate patients lost to follow-up and to establish whether they were still alive. Their detailed survival data were compared with the age- and sex-matched normal population. Collaboration with specialist centers dealing with adult congenital heart disease nationally provided corresponding incidence data relating to the changing prevalence over time of secondary pulmonary valve replacement after Fallot repair. In the second part of the study, a subset of patients were chosen at random to represent those free from subsequent pulmonary valve replacement. These patients of all ages were assessed thoroughly with conventional noninvasive imaging and functional modalities to characterize their cardiac morphology and function. The currently published literature focuses primarily on patients who need reintervention, and less is formally documented about those who are “well.” We also hoped to identify those characteristics that would suggest that the initial surgical repair has proved definitive, that is, patients with normal exercise capacity who are still free from pulmonary valve replacement at 35 years of age. The morphological characteristics of these patients with what seems to be an ideal outcome may serve as guide for today’s surgeons and provide a good substrate for further longitudinal studies.
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